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China's building stock estimation and energy intensity analysis

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ABSTRACT

Reliable and objective data regarding building stock is essential for predicting and analyzing energy demand and carbon emission. However, China's building stock data is lacking. This study proposes a set of China building floor space estimation method (CBFSM) based on the improved building stock turnover model. Then it measures China's building stocks by vintage and type from 2000 to 2015, as well as building energy intensity (national level and provincial level) and energy-efficient buildings. Results showed that total building stocks increased significantly, rising from 35.2 billion m^2 in 2000 to 63.6 billion m^2 in 2015, with the average growth rate 4.0%. The deviations were well below 10% by comparing with *China Population Census*, which validated the reliability of CBFSM and the results. As for energy intensity, urban dwellings and rural dwellings showed relatively stable and increasing trend respectively. The commercial building energy intensity saw a downward trend during “12th Five Year Plan” period. This indicated the effectiveness of building energy efficiency work for commercial buildings since 2005.38.6 billion m^2 residential dwellings and 5.7 billion m^2 commercial buildings still need to be retrofitted in future. CBFSM can overcome shortages in previous studies. It can also provide Chinese government with technical support and data evidence to promote the building energy efficiency work.

1. Introduction

China has become the world largest CO_2 emitter with its increasing energy consumption since 2006 with 29.1 billion tons CO_2 emissions (IPCC, 2014). China faces the serious challenges on energy conversation and emission reduction, due to China's primary energy consumption grew at an average annual rate of 5.6%, 2.9 times that of the world over the same period from 1978 to 2015(IEA, 2013). The building sector is one of the three largest energy-consuming sectors, in addition to industry and transportation sectors, and is also an important source of GHG emissions (Zhang and Wang, 2017). The building sector consumes approximately 40% of total energy use in most developed countries (IEA, 2013). From 2000 to 2014, China's building energy consumption (BEC) increased 1.7 times, rising from about 301 to 814 million tons standard coal equivalent (tce) (Huo et al., 2018a,b,c), and is expected to increase further to 35% of the national total energy consumption by 2020 (Zhou and Lin, 2008). If accounting for the energy consumption of building materials manufacturing and excavation, the percentage will increase to 46.7% (Cai, 2014). Therefore, the energy saving and emission reduction in the building sector faces huge challenges and pressure.

In this context, China has performed much building energy efficiency (BEE) work, since the 1980s, such as the implementation of BEE codes for new buildings, existing building retrofits, and the application of renewable energy to buildings. However, over the past 30 years, the BEE work has been used to control the energy performance of the building components (e.g., enclosure structures, equipment systems, etc.) and it is the performance-based BEE work. Little attention has been paid to the building energy intensity and actual energy consumption. The actual energy saving outcome of the BEE work can therefore not be accurately calculated. Currently, China's 13th Five-Year Plan (FYP) (2016–2020) first proposed the cap control target of energy consumption. After that, the Ministry of Housing and Urban-Rural Development (MOHURD)'s 13th FYP for building energy efficiency and green building development proposed a mitigation action plan of

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improving urban residential energy performance 20% by the year of 2020 based on the 2015 level. Obviously, accurate and objective BEC data is the premise to carry out cap control, set BEC baseline, calculate actual energy savings and predict carbon peak value. However, there exists a significant shortage of energy consumption data in China's BEE field. The root cause is that China's energy consumption in the building sector are not counted as a separate type of energy consumption, but being mixed in other sectors in China's statistical system. More importantly, the lack of a unified calculation method and inconsistent data source for BEC are critical obstacles to obtain authoritative and high recognized BEC data (Cai, 2011; Cai et al., 2009). Such shortcomings resulted in the "heterogeneous" of current BEC in China.

In addition to the historical BEC data, the historical building floor space (BFS) is also an important factor for people to understand the actual energy consumption in the building sector (Huo et al., 2018a; Huo et al., 2018b). The building stock plays a significant role in actual energy savings calculation, energy consumption prediction, and carbon emission projection (Liu et al., 2017). Recent years, with the rapid urbanization, growth of household income and growth of the service sector (IEA, 2007), great quantities of buildings are being constructed and the total BFS in China increased from 10.2 billion m^2 in 1980 increased to 52.7 billion m^2 in 2008. Nearly half of the world's new building construction now is in China, which is about two billion m^2 of new buildings per year (NBS, 2014). It is projected that 800 million m^2 of new urban residential floor space will be built in China annually through to 2030 (IEA, 2007). The construction and operation of such great amount of buildings causes plenty of resources and energy consumption and eventually they are demolished with massive building wastes generation. Apart from that, the building stocks by vintages (i.e., the floor space of the existing buildings those were constructed during different periods, e.g., 1950–1959) are essential for the government to understand the situation of floor area of energy efficient buildings and set energy efficient retrofit plan. Unfortunately, there is not a set of general and authoritative time-series data on China's building stocks, demolished buildings and newly built buildings to date, which hinders China's BEE work. Therefore, quantifying the China's BFS and obtaining good quality and defensible data has become the key issues needs to address urgently.

In this context, research on macro BFS has drawn scholars' attention gradually. Current scholars adopted the BFS as the driving force to predict future energy consumption and material demand of China's buildings (Dong et al., 2017; Hu et al., 2010a; Zhou and Lin, 2008). They mainly obtained the base year BFS directly from *China Statistical Yearbook*, and then predicted the future BFS according to some assumptions and the national development plan (Hong et al., 2016; McNeil et al., 2016; Yang et al., 2017; Zhou et al., 2013). Obtaining BFS data directly from the *China Statistical Yearbook* is highly problematic, because there exist deficiencies in China's statistical system, such as the change of the statistical range and change of the statistical caliber over time, together with the incompleteness of time series data and other factors.

To address these gaps, we have developed a *Statistical Yearbook-energy balance sheet* based splitting method to estimate China's BEC and obtained the objective historical BEC data (Huo et al., 2018c). Based on our previous work, this study aims to conduct the four following tasks. Firstly, we extensively analyze the existing deficiencies of various statistical indictors pertaining to the floor space in *China Statistical Yearbook* by systematically combing the statistical reporting system related to the floor space in China over time. Secondly, we establish China building floor space estimation model (CBFSM) based on the improved building stock turnover model. Thirdly, we estimate the historical data of the building stocks and demolished buildings by type and vintages from 2000 to 2015 adopting CBFSM. Fourth, we validate the result of this study by comparing with the data from *China Population Census* and other studies. Finally, we calculate the building energy intensity by type and estimate the size of the energy efficient buildings. The proposed method (CBFSM) not only eliminates the deficiencies of inconsistent statistical caliber in the statistical yearbook, but also derives the authoritative and high-quality BFS data, and this can provide accurate and valuable data support for the government to determine material and energy demand, set reasonable energy efficiency policy and promote building energy saving work.

The rest of this paper is presented as follows: Section 2 is the literature review on BFS related research and review on existing deficiencies regarding BFS in *China Statistical Yearbook*. Section 3 provides the methodology. Section 4 shows the calculation results and validation, and Section 5 presents the analysis and discussion. The last section offers the conclusions and future directions for study.

2. Literature review

2.1. Review on building floor space related research

Building stocks are the main driving force for energy consumption and material demand in the building sector. The building stock has long lifespan characteristics, and many scholars calculated the volume of the building stock when they forecasted the energy and resource demands. For example, Ref (Müller, 2006). developed an archetypal dynamic material flow analysis (MFA) model and used this model to calculate and predict the housing stock of Netherlands from 1900 to 2100, and then projected the resource demands and waste emissions. Bergsdal et al. and Gallardo et al. then adopted this model to estimate the residential building stock of Norway (Bergsdal et al., 2007) and Chile's building stock calculation (Gallardo et al., 2014) respectively. Pauliuk et al. developed a comprehensive model by integrating the life cycle assessment techniques to this dynamic MFA model to measure the building stock (Pauliuk et al., 2013). On this basis, Sandberg et al. then utilized an extended segmented model to estimate the demolished and renovated residential building stock of Norway (Sandberg et al., 2014). Apart from that, Moura et al. adopted a dynamic stock-driven model to simulate and forecast the evolution of building stocks of the United States for 120 years (Moura et al., 2015).

As for China's building stock, Hu et al. adopted dynamic MFA model to calculate and predict the urban and rural housing stock of China, but did not identify the commercial BFS (Dong et al., 2017; Hu et al., 2010a, 2010b; 2010c, 2010d). Yang et al. studied the statistic method for China building energy consumption, and they directly used BFS data from the *China Statistical Yearbook* to calculate the energy intensity (Yang et al., 2017). Zhou et al. developed a bottom-up Long-range Energy Alternatives Planning (LEAP) model to project future energy consumption of end-use sectors in China, including the building sector (Zhou and Lin, 2008). Fridley et al. adopted the same method as Zhou et al. and calculated the BFS in China from 2005 to 2020 (Fridley, 2008; Hong, 2009). This processing method is unreliable, because the floor space of the industrial sector is included when subtracting residential floor area from the total building floor space. Ecom et al. studied China's long term building energy demand with macroeconomic model (Ecom et al., 2012). Hong et al. conducted a study on China building floor area (Hong et al., 2016). However, the lack of publicly available detailed data relating to inputs and assumptions, as well as the complex of the underlying algorithms, renders the derived results problematic. Additionally, many other scholars studied China building energy consumption-related floor space: Zhou and Lin (2008), McNeil et al. (2012), Zhou et al. (2013), and they directly obtained the historical BFS data from the *China Statistical Yearbook* to make predictions.

From the overview on other scholars' studies, this study identified some drawbacks in the existing research associated to China's building stock and demolished buildings. (1) The residential building stock was directly obtained from *China Statistical Yearbook* (Hu et al., 2010a; Zhou et al., 2003; Zhou and Lin, 2008), which is highly problematic and unreliable due to the deficiencies in China's statistical system. This is due to the change of the statistical range and the change of the statistical caliber over time, as well as the incomplete time series data and other factors. (2) Previous scholars did not separate the industry floor space from the commercial floor space when directly subtracting residential floor area from the total building floor space, so the commercial BFS they obtained actually contains industry BFS (Zhou and Lin, 2008; Fridley, 2008). This would lead to the overestimation of commercial BFS. (3) The amount of the demolished buildings was merely obtained through a small-scale sample survey (Liu et al., 2014). The data at the national level are still unavailable. (4) None have obtained the data on building stocks and demolitions by vintage to date.

This paper tries to fill these gaps, and the contribution of this study is mainly as follows: (1) It extensively analyzes the existing deficiencies regarding statistical indicators related to the BFS in the *China Statistical Yearbook*, which can provide readers a better and deeper insight in understanding the *China Statistical Yearbook*. (2) It attempts to propose a set of more universal and general China building floor space estimation method (CBFSM) based on the improved building stock turnover model. The CBFSM model can overcome the shortages of previous studies and provide a very concise and practical means of acquiring a set of consistent China BFS data based on the authoritative data source. (3) It measures China historical building stocks, demolished buildings, and newly built buildings by type and vintage (construction periods) from 2000 to 2015, adopting the CBFSM, as well as building energy intensity national level and provincial level. The model result is more reliable and defensible compared with *China Population Census* and other studies, and which is valuable to governmental officials in terms of energy planning, or energy policy evaluation and carbon emission peak value prediction in the building sector.

2.2. Existing deficiencies for the indicators related to BFS listed in China statistical yearbook

(1) Large differences exist between two statistical calibers on the urban residential floor space. The total floor space of residential buildings (year-end) is 40%–50% the residential floor space derived according to the per capita floor space of residential buildings. The reason is that the statistical scope of the per capita floor space of buildings is family households in urban area, but it ignores the collective households, which results in the higher results. The statistical scope of the total floor space of buildings (year-end) is *city* level (before 2001) and it extends to *city* and *county* level during 2001–2006, but the *town* level data is missing. This is why the result calculated using this indictor is lower. Therefore, using either of these two indicators to calculate BFS is unreliable. This study will use the *actual* urban residential floor space per capita to calculate the building stock for the base year (Huo et al., 2018a).

(2) The data on the urban commercial floor space are unavailable in the statistical yearbook (Huo et al., 2018a). There are no direct statistical data for the urban commercial floor space (including *city* and *county*). In fact, the difference between total floor space of buildings (year-end) in urban areas and total floor space of residential buildings (year-end) in urban areas includes two categories: commercial floor space and industrial floor space (also called *productive buildings floor space*).

There are other deficiencies. The statistical caliber on the total floor space of urban buildings (year-end) are inconsistent over time. The time series data regarding most of the statistical indicators are incomplete. There are different statistical channels for the floor space of buildings completed (Huo et al., 2018a).

3. Methodology

CBFSM is the methodology which is established for the first time in this study. It can be used to quantify the annual building stock and demolished buildings by vintage in a given year. In the study, the existing buildings constructed in previous vintages in a given year can be estimated. In other words, how much buildings constructed in different previous vintages (e.g. before 1949, 1950–1959, 1960–1969, 1970–1979, 1980–1989, 1990–1999, 2000–2009 and 2010–2015) survived during 2000–2015. And the newly built buildings during a given year can be estimated. Technical parameters such as buildings' lifetime and the demolition rate are expressed by means of the probability functions.

3.1. CBFSM model description

In this study, we set 2000 as the base year. The rural residential building floor space $S_{\mathrm{rural}(t)}$ in year t can be calculated as follows:

$$S_{\mathrm{rural}(t)} = SP_{rural(t)} \times P_{\mathrm{rural}(t)} \tag{1}$$

where $P_{\mathrm{rural}(t)}$ is the urban population in year t, $SP_{\mathrm{rural}(t)}$ represents the per capita floor space of residential building in rural areas in year t.

To eliminate the deficiencies mentioned in Section 2, this study introduces the *actual* per capita floor space of residential building by considering the collective households. The *actual* per capita floor space of residential building in urban areas $SP_{act(t)}$ in year t can be calculated as follows:

$$SP_{act(t)} = (P_{household(t)} \times SP_{household(t)} + P_{\mathrm{collective}(t)} \times SP_{\mathrm{collective}(t)})/\ \left(P_{household(t)} + P_{\mathrm{collective}(t)}\right) \tag{2}$$

where $P_{household(t)}$ denotes the sample population of the family households in urban areas in year t, $SP_{household(t)}$ represents the per capita floor space of the family households in urban areas in year t, $P_{\mathrm{collective}(t)}$ is the sample population of the collective households in urban areas in year t, $SP_{\mathrm{collective}(t)}$ represents the per capita floor space of the collective households in urban areas in year t. The estimation of the per capita floor space of the collective households is according to the "*Several Opinions on the Standard of College Students' Apartment Construction*" issued by the Ministry of Education of China (MOE, 2001). The urban residential building floor space $S_{\mathrm{urban}(t)}$ in year t then can be calculated as follows:

$$S_{\mathrm{urban}(t)} = SP_{act(t)} \times P_{\mathrm{urban}(t)} \tag{3}$$

where $P_{\mathrm{urban}(t)}$ is the urban population in year t.

The commercial building stock in the base year is calculated according to full caliber, including urban commercial buildings and rural commercial buildings. The rural commercial buildings floor space can be calculated directly, adopting statistics data. The urban commercial building floor space can be referenced the data of our previous work (CABEE, 2017), which has split the commercial and industrial BFS according to the ratio of the industrial area of land used for urban construction and the commercial area of land used for urban construction in the *China Statistical Yearbook*.

The building stock in a given year is calculated according to the building stock turnover model as follows:

$$Stock_t^{vin} = Stock_{t-1}^{vin} + New_t^{vin} - Retire_t^{vin} \tag{4}$$

where $Stock_t^{vin}$ represents the building stock in a given year t and vintage vin ($vin =$ before 1949, 1950–1959, 1960–1969, 1970–1979, 1980–1989, 1990–1999, 2000–2009, and 2010–2015). New_t^{vin} Denotes the newly built building in year t and vintage vin; and $Retire_t^{vin}$ refers to the retired buildings during year t and vintage vin.

In the model, when a building reaches the end of its useful life it is considered as demolished. So the demolished/retired buildings actually means "buildings exiting the model's stock of inhabited buildings" (Sartori et al., 2016). The assumed average lifetime is important for the model results (Müller, 2006). In line with the references (Hong et al., 2016; Hu et al., 2010d), the normal distribution probability P_t^{vin} of the retired buildings in the given year t and vintage vin can be shown as follows:

$$P_t^{vin} = \frac{1}{\sqrt{2\pi}\sigma}\int_0^{lifetime_t^{vin}} e^{-\frac{\left(lifetime_t^{vin}-\mu\right)^2}{2\sigma^2}} dt \tag{5}$$

where $lifetime_t^{vin}$ represents the lifetime of buildings in year t and vintage vin; μ denotes the average lifetime of the building stock; σ represents the standard deviation; p represents output cumulative probability. In this study, the configuration of μ is according to the principle of making the deviation of the final results minimum, which is shown in the optimization model (8); σ is assumed to be one third of the average building lifetime (Hu et al., 2010d).

The demolished buildings in a given year t and vintage vin, are defined as the initial building stock in a given year $t-1$ in vintage vin multiplied by cumulated demolition rate (Komiyama et al., 2008), which is shown as follows:

$$Retire_t^{vin} = Stock_{t-1}^{vin} \times \frac{P_t^{vin} - P_{t-1}^{vin}}{1 - P_{t-1}^{vin}} \tag{6}$$

where $Retire_t^{vin}$ represents the retired buildings which were retired in year t and vintage vin; $Stock_{t-1}^{vin}$ refers to the buildings which were survived in year $t-1(t \geq 2001)$ and vintage vin. The segment of the vintages is consistent with the percentages of building stocks in *China Population Census*. The values of $Stock_{2000}^{vin}$ can be assigned according to corresponding vintage ratio in the 2000 *China Population Census*.

The newly built buildings are defined as the building constructed after 2000. The newly built residential BFS after 2000 is derived from *China Statistical Yearbook*, but adjusted by adjustment coefficient. As for urban residential new construction, an adjustment coefficient k_t is need to offset the lower deviation of the new construction due to the incomplete statistical caliber, as shown in Equation (7).

$$New_t = New_{yearbook} \times k_t \tag{7}$$

The key principle is to make the deviation minimum. The deviation calculation is listed in the appendix.

3.2. Data source and research scope

The raw data regarding to the base year (i.e., 2000) in this study are obtained from the *China Statistical Yearbook* and *China Urban and Rural Construction Statistical Yearbook*. The percentage of the buildings in different vintages in the base year are retrievable from the 2000 *China Population Census*. Considering only the BFS related data from the following four sources (i.e., the fifth *China Population Census*, the sixth *China Population Census*, the *1% population sample survey* (also called *Micro Census*) in 2005 and the *1% population sample survey* in 2015 can be obtained, we determine the appropriate research time series interval should be 2000–2015.

4. Results and validation

4.1. Results of China's building stock

According to equations (1)–(7) above, China's building stock by types (i.e., urban dwelling, rural dwelling and commercial building) and by vintage from 2000 to 2015 are derived, which are shown in Fig. 1.

Fig. 1 shows that, from 2000 to 2015, the urban residential BFS saw a dramatic increase; more than doubling, from 10.6 billion m^2 to 27.4 billion m^2. The rural residential BFS did not experience a dramatic change, with that figure just growing from 20.1 billion m^2 to 25.3 billion m^2 during the whole period, although it just accounted for the lowest percentage, below 18%. The commercial buildings constructed between 2000 and 2009 increased more than ten times, from 0.3 billion m^2 in 2000 to 3.4 billion m^2 in 2015. The dominant component of the urban residential building stock from 2000 to 2015 were buildings constructed after 2000. Those buildings showed a dramatic increase, more than ten times, from 0.8 billion m^2 to 19.1 billion m^2 during the whole period. Commercial buildings constructed after 2010 also showed a significant growth, rising from 0.5 billion m^2 in 2010 to 3.9 billion m^2 in 2015.

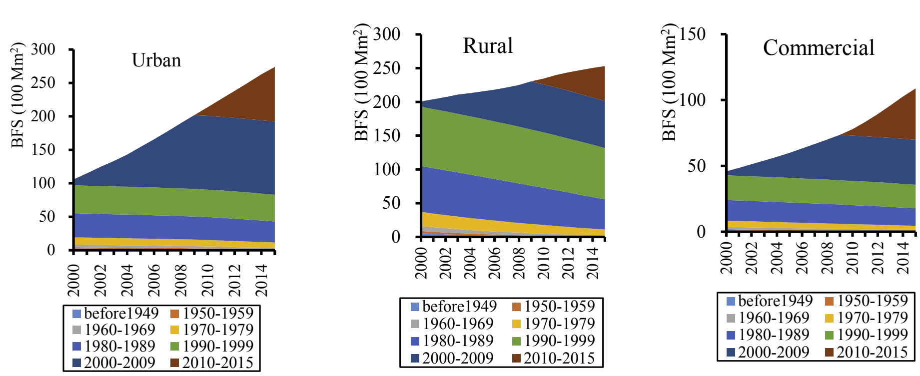

Fig. 1. The composition of the building stock by vintage from 2000 to 2015.

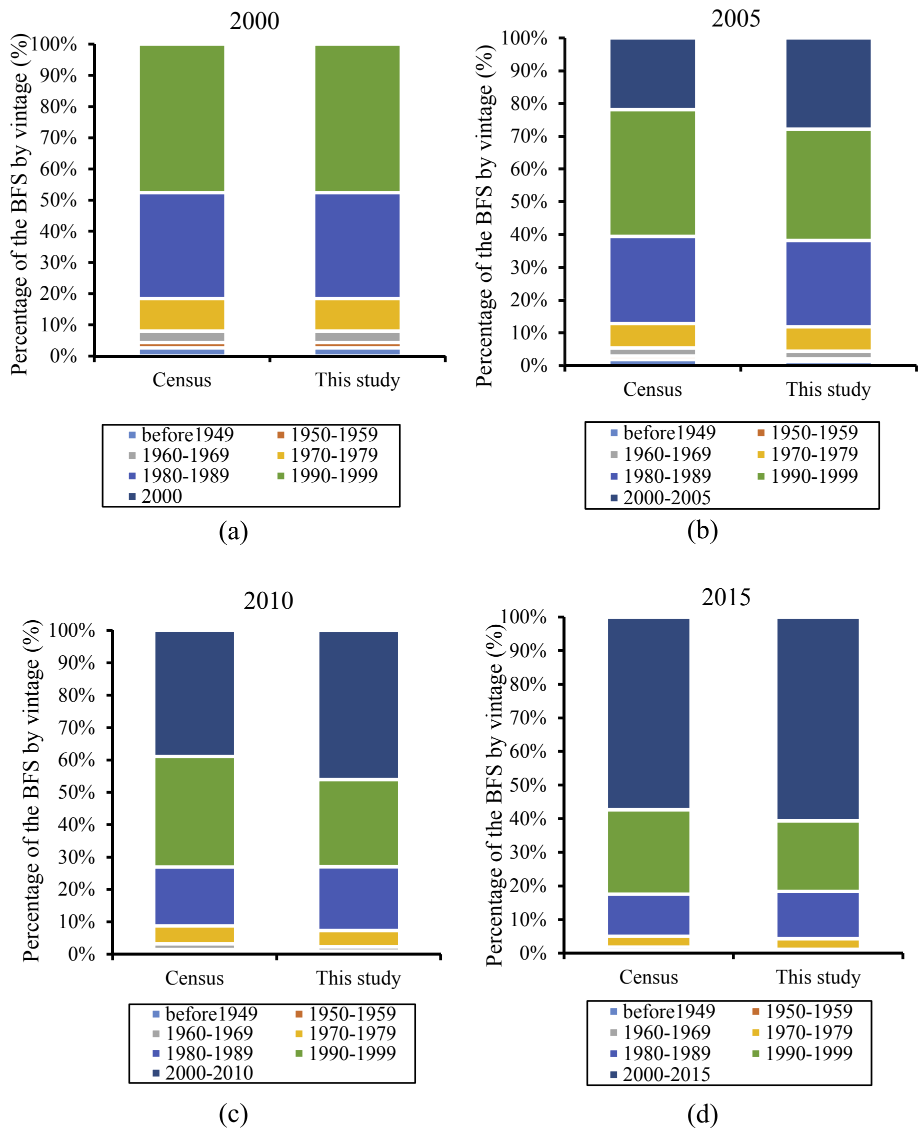

Fig. 2. The comparison between this study and the *China Population Census* in terms of percentages of the building stock in each vintage.

The possible reason may be that the Chinese government emphasized urbanization after 2010. During the 12th FYP period, the Chinese government emphasized using urbanization as a powerful engine to promote economic development and to remake the economy in an environmentally friendly way. The rapid urbanization process contributed to the swift growth of the urban residential building stock.

4.2. Model validation

To validate the reliability of the results of this study, the comparison between the total building stocks and the percentages of different vintages obtained in this study and the counterparts in the *China Population Census* are shown in Fig. 2. Due to unavailability of the other years' data in *China Population Census*, we just compare the data in four years: 2000, 2005, 2010 and 2015. The fifth and sixth *China Population Census* are 2000 and 2010 *China Population Census*, respectively. The 2005 *Micro Census* and 2015 *Micro Census* are also authoritative data sources in China like *Population Census*. In both the *Population Census* and the *Micro Census*, there are the percentages of the building stock by vintage.

As shown in Fig. 2, the deviation of the percentages of the building stock in each vintage between this study and the *China Population Census* are all well below 10%. The comparison shows that the results of this study and the *China population census* data are very close to each other. This can indicate the robustness and reliability of the derived results in this study and feasibility of the CBFSM model.

5. Analysis and discussion

In this section, the changing trend of China's building stock evolution from 2000 to 2015 will be analyzed. And then the building energy intensity and the energy efficient buildings will be measured and analyzed.

5.1. Analysis of the building stock

5.1.1. Status quo of China's building stock in 2015

Using the results from Fig. 1, the composition of the building stock by type and vintage in 2015 can be drawn, as shown in Fig. 3.

As shown in Fig. 3, China's total building stock was 63.6 billion

m^2 in 2015. Of this, the urban dwelling stock accounted for the largest (43%), followed by rural dwelling stock (40%) and commercial building stock (17%). Fig. 2 shows that, in 2015, buildings constructed after 1990 accounted for more than 80% of the total building stock, and buildings constructed after 2000 represented 60.6% of the total building stock. The possible reasons might be the rapid urbanization process (Fan et al., 2017) and households' increasingly diversified housing needs. In line with the *China Statistical Yearbook*, the urbanization rate saw a significant growth, rising from 36.2% in 2000 to 56.1% in 2015 (NBSC, 2016). To accommodate the migrant and non-migrant workers, China's construction activities these years were massive. Besides, the households demand for new houses have soared since China entered material affluent society from economic shortage stage. With the increase of people's disposal income, they do not want to live in the old house, instead they prefer to buying new dwellings especially for young people.

5.1.2. Evolution of the building stock and composition

In line with the results in Fig. 1, the building stock turnover dynamics from 2000 to 2015 are shown in Fig. 4.

Fig. 4 shows a good description of the building stock turnover process. For example, in 2005, the building stock in 2005 was 42.98 billion m^2 which equals building stock in 2000 minus the amount of demolitions from 2001 to 2005 and plus the amount of new constructions from 2001 to 2005. The building stock turnover process is also applied to other years. As shown in Fig. 4, the total building stocks in China witnessed a significant upward trend, from 35.2 billion m^2 in 2000 to 63.6 billion m^2 in 2015. From 2000 to 2015, the demolished buildings increased from 2.3 billion m^2 during 10th FYP period (2001–2005) to 3.6 billion m^2 during 12th FYP period (2011–2015). And during the referenced period, the newly built buildings saw a fluctuation and increased from 10.1 billion m^2 during 10th FYP period (2001–2005) to 14.6 billion m^2 during 12th FYP period (2011–2015). The increasing population is an important driving force for the rapid new construction. The population in urban areas increased 31.2 million, rising from 45.9 million in 2000 to 77.1 million in 2015 (NBSC, 2016). Another important cause the improvement of living standards (Zhang et al., 2015); the annual per capita disposable income of urban households climbed more than five folds, rising from 6280 yuan to 31.2 thousand yuan from 2000 to 2015 (NBSC, 2016). Besides, the rapid demolition of buildings during these years may have been the driving forces for the increased new construction.

Fig. 5 shows the composition of China's building stock by type and the percentage of the newly built buildings after 2000 from the period of 2000–2015.

As Fig. 5 shows, the annual growth rate of the BFS was 4.0% throughout the whole period. The annual growth rate of the urban residential BFS was the highest: 6.6%, and the figure for the commercial BFS and rural residential BFS was 6.0% and 1.6%, respectively, during the period 2000–2015. The annual new construction rate was about 5% during 2000–2015. The percentage of the accumulated newly built buildings after 2000 increased from 5.4% in 2001 to 61.2% in 2015.

5.1.3. Comparison with other studies as the building stock

The comparison of the three types of BFS with China Building Energy Use (CBEU) (BERC, 2017), which is shown in Fig. 6.

As shown in Fig. 6, the rural residential building stock and commercial building stock are very close to CBEU's results. This can verified the reliability of our results. The urban residential building stock were higher that CBEU'S result. This might be due to the changing and inconsistent caliber of the statistical data as mentioned in section 2. We made the correction by considering the collective households in addition to the family households in our calculation of the base year data. This can improved the accuracy of our estimation results.

5.2. Analysis on the building energy intensity by type

In this section, the energy intensity of buildings by type will be calculated and analyzed. Building energy intensity in this study means building energy consumption per unit building area. The BEC data of our previous work (Huo et al., 2018a,b,c) will be used to calculate the building energy intensity combined with the BFS data obtained in section 4.

5.2.1. Urban and rural residential building energy intensity

According to the results in Fig. 1 and China Association of Building Energy Efficiency (CABEE)'s energy consumption data (Huo et al., 2018a,b,c), the urban residential building energy intensity can be obtained, which is shown in Fig. 7.

As shown in Fig. 7, the energy consumption per unit floor area of

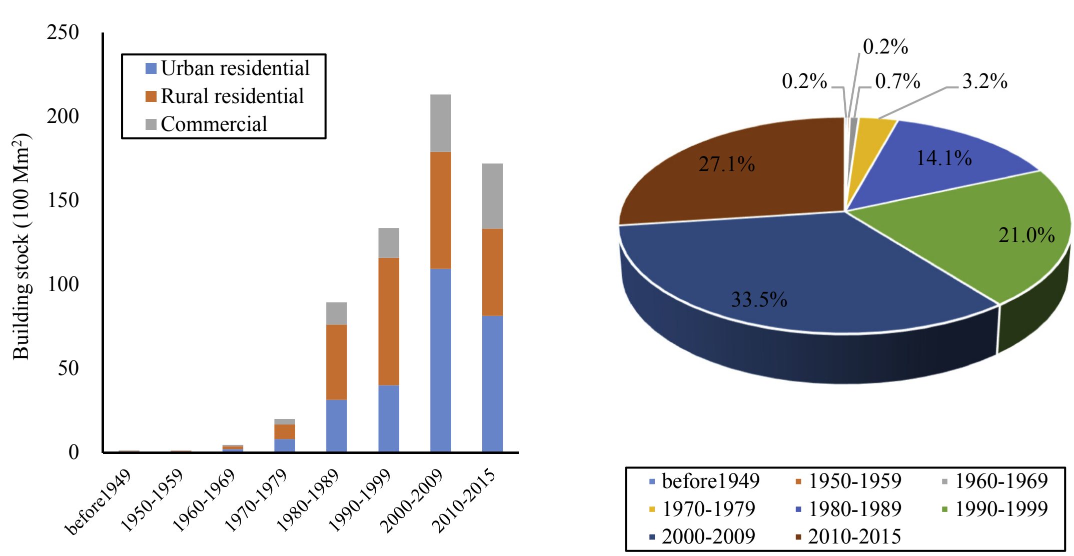

Fig. 3. The percentage composition of the building stock by type and vintage in 2015.

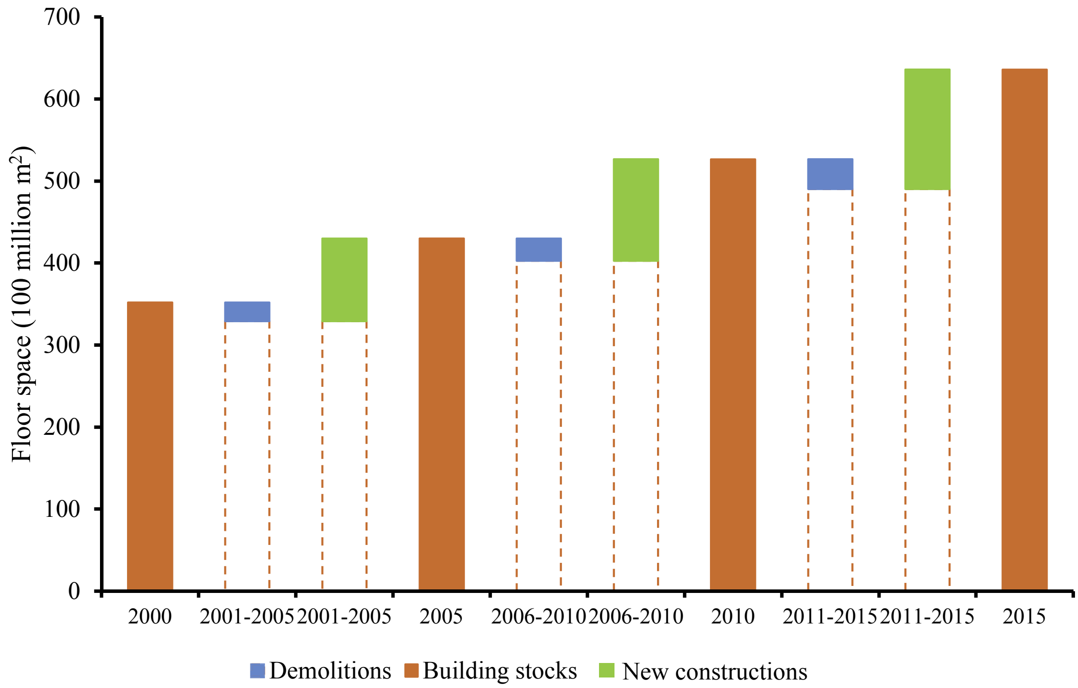

Fig. 4. China's building stock turnover dynamics during 2000–2015.

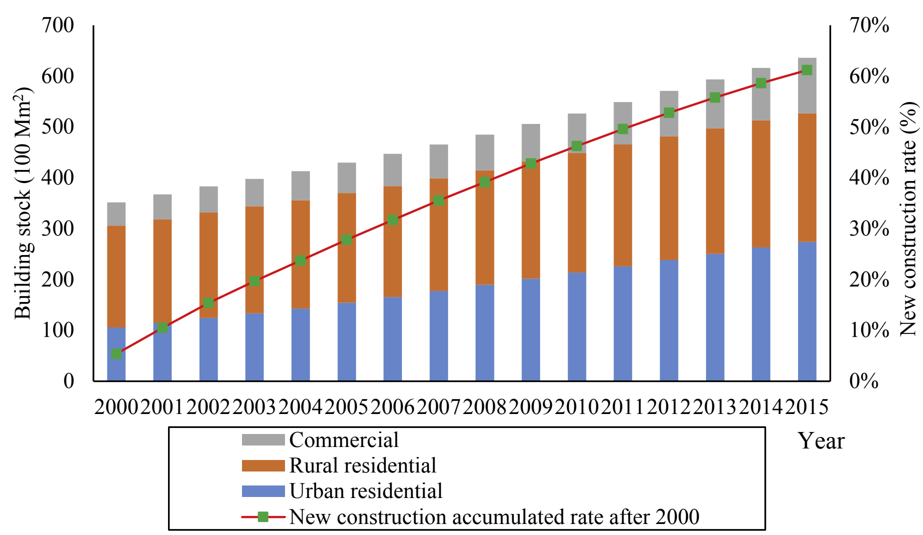

Fig. 5. The composition of the building stock by type during 2000–2015 and the fraction of building area constructed after 2000.

urban residential buildings remained relatively stable throughout the whole period from 2000 to 2015, and the downward trend after 2007 was more obvious. In 2015, the energy consumption per unit area of urban residential buildings was 70.67 kwh/m^2. In comparison, the energy intensity of rural residential buildings has increased more than twice, rising from 22.38 kwh/m^2 in 2000 to 48.32 kwh/m^2 in 2015, with an average annual increase of 5.5%.

The explanations for this phenomenon in urban residential energy intensity are as follows. Since 2005, the supervision and inspection of energy efficient codes for new buildings has been enhanced. Through the special supervision and inspection, the implementation rate of energy-saving codes in the construction phase of new buildings in China has greatly increased from 24% in 2005 to more than 95%. By the end of 2015, the implementation rate of energy-saving codes for urban newly-built buildings has reached 100%, an increase of 4.6% over 2010. In 2013, the "*Green Building Action Plan*" was forwarded by State Council, setting "ten projects to promote the development of green buildings", such as green building evaluation marking system, green building design special supervision system, water-saving appliances and solar energy building integrated promotion system have all been widely implemented and well performed.

The main reasons for the rural residential building energy intensity increase are as follows: (1) With economic development, the living conditions of rural residents have improved significantly, and the number of household appliances has increased exponentially. For example, the average number of air-conditioners per hundred households in rural households has increased from 1.3 in 2000 to 38.8 in 2015. an increase of 29.8 times. The number of refrigerators increased from 12.3 in 2000 to 82.6 in 2015, an

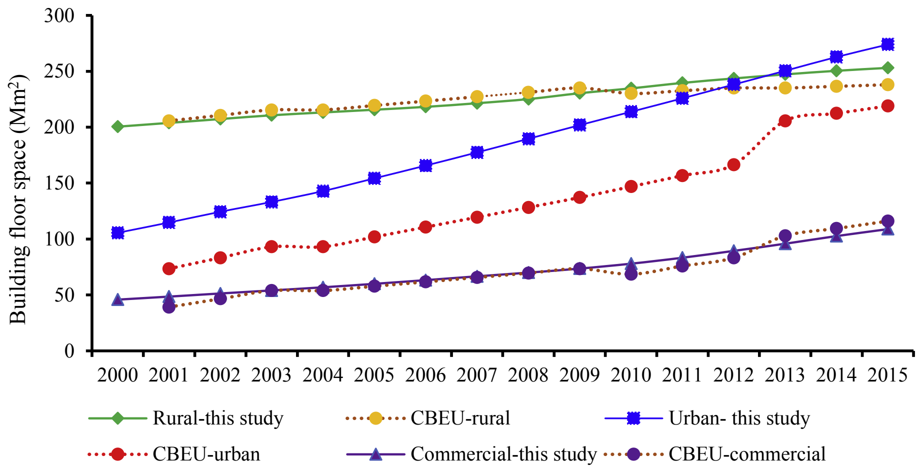

Fig. 6. Comparison with other studies on building stock from 2000 to 2015.

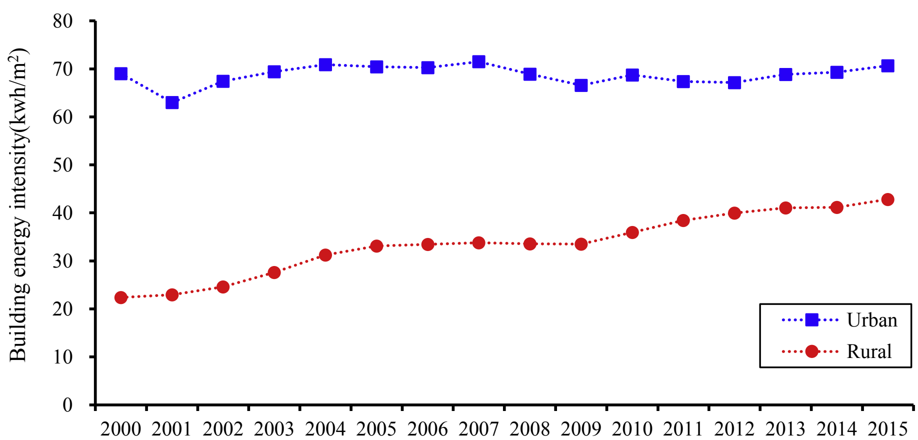

Fig. 7. The energy intensity of the urban/rural residential buildings.

increase of 6.7 times. The dramatic increase is also applied in clothes washer and color TV and so on. The increase in ownership of household electrical appliances has brought about increasing demand for energy use per unit floor area. (2) The biomass energy is the main fuel for cooking and spacing heating in traditional rural areas, and the non-commercial energy accounts for a large proportion in rural areas, 56% in 2004. With the development of rural economy, the living conditions of rural residents have increased, more and more rural residents move into new buildings. With the traditional life style changing, the number of households using biomass for cooking has decreased significantly and rural household energy has changed from non-commercial energy to commercial energy. According to the data from the IEA, the total rural biomass energy consumption in China has been declining annually, and the proportion of non-commercial energy consumption has dropped by 20% from 2001 to 2014. More and more non-commercial energy has been replaced by commercial energy, which has also contributed to the increase in energy consumption per unit area of rural buildings. (3) Compared with urban buildings, the BEE work in rural areas has not yet become the focus of rural development. The "*Special Plan for Building Energy Efficiency in* 12th *FYP*" pointed out that during the "12th FYP" period, "the BEE of rural areas in most provinces and cities has not yet officially started". It can be seen that the energy saving of rural buildings in China is still at an exploratory stage, without specific energy efficient path.

5.2.2. The energy intensity of the commercial buildings

Based on the results in CABEE's energy consumption data (Huo et al., 2018a,b,c), the commercial energy intensity can be obtained, which is shown in Fig. 8.

As shown in Fig. 8, the change in energy consumption per unit building area of commercial buildings can be divided into three distinct stages. (1) During the "10th FYP" period, energy consumption per unit area of commercial buildings increased annually from 126.8 kwh/m^2 to 174.6 kwh/m^2 from 2000 to 2005, with an average annual increase of 7.8%. (2) During the "11th FYP" period, the energy consumption per unit building area remained relatively stable, fluctuating slightly with the fluctuation of economic growth, and the wavelet valley appeared in 2007. (3) Since the "12th FYP", the energy consumption per unit building area of commercial buildings saw a downward trend, declining from 175.1 kwh/m^2 in 2011 to 158.1 kwh/m^2 in 2015.

5.2.3. The building stock and energy intensity in China's different provinces and climate zones

The China Association of Building Energy Efficiency (CABEE) launched the Energy Consumption Statistics Professional Committee in 2015 aiming to establish China's BEC and carbon emission database. In the first stage, the committee developed the China's building energy consumption calculation method (CBECM) and quantified the energy consumption in China's building sector (Huo et al., 2018a,b,c). This study is the second module of the database:

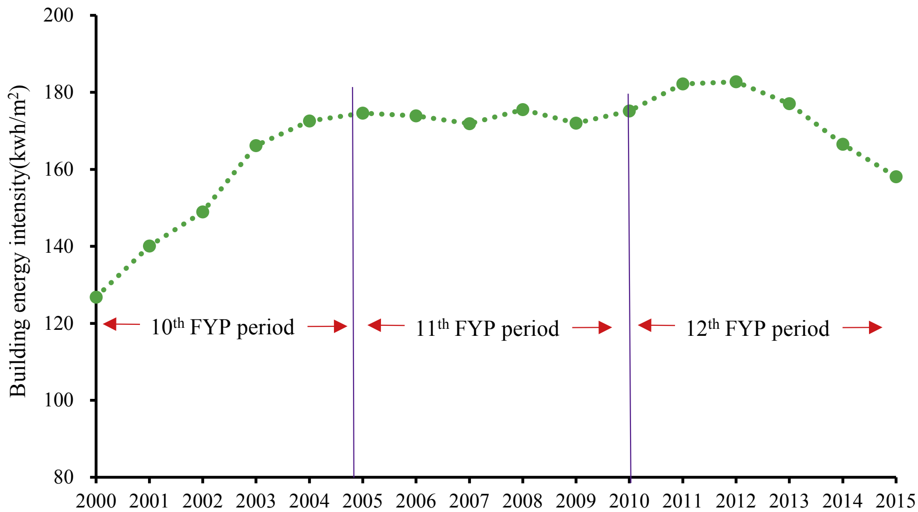

Fig. 8. The energy intensity of the commercial buildings.

building floor space module. The building stock and energy intensity by different provinces and climate zones are shown in Fig. 9 and Fig. 10.

As shown in Fig. 9, the size of the building stock in Shandong province was the largest, reaching 4607 million m^2 in 2005. The provinces with high building stock are mainly located in Hot summer and cold winter zone and hot summer and warm winter zone. In China's western and northern areas, which are mainly located in severe cold and cold zones, the building stocks were less than 2000 million m^2 in 2015. In Fig. 10, it is obviously that the high-energy intensity provinces are mainly located in northern China. This is because most urban areas in north China were China's northern area covered by the district heating system, which helps to maintain 20 °C indoor temperature. Generally, the heating period for district heating is from November 15 to March 15 the following year in most north provinces. Inner Mongolia and other colder provinces is relative longer with the heating period. This is why the energy intensity in Inner Mongolia ranked the second in China, approximately 249.0 kwh/m^2. The energy intensity is Beijing is the highest, 270.1 kwh/m^2 in 2015, due to its well-developed economy and the service sector. The building energy intensity in those provinces in Hot summer and cold winter zone were lower because their less demand for heating in winter. Guangdong's energy intensity was higher than its neighbors due to its well-developed economy.

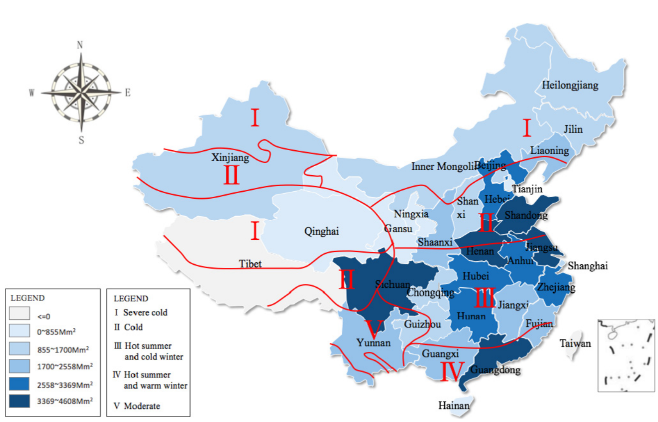

Fig. 9. The building stock in China's different provinces and climate zones in 2015.

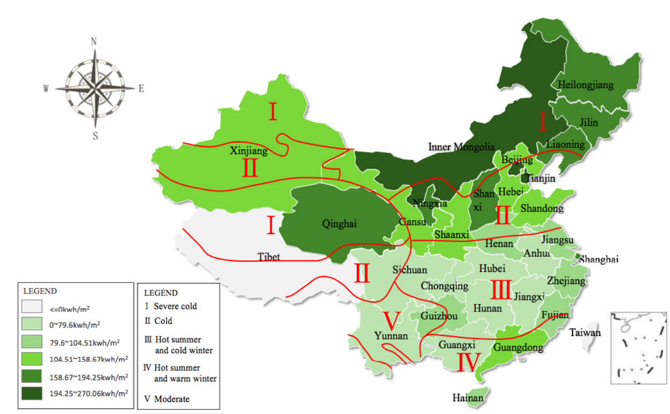

Fig. 10. The building energy intensity in China's provinces and climate zones in 2015.

5.2.4. Comparison with other studies on the energy intensity

The comparison with other studies' results are shown in Fig. 11. There are only one year data in some studies.

As shown in Fig. 11, three dashed lines with plots are this study's results. Ref (1)'s results are China's commercial building energy intensity data (Zhou, 2011). Obviously, Ref (1)'s results were lower than our results. This is because, in their study, the commercial floor space were obtained by subtracting total floor space of residential buildings (year-end) in urban areas from total floor space of buildings (year-end) in urban areas. This processing method is problematic, because the derived commercial floor space contains industrial floor space (also called productive buildings floor space). This is the root cause of their lower energy intensity. Ref (2) (Ecom et al., 2012)'s residential energy intensity in 2005 was close to our residential energy intensity. Ref (2)'s residential energy intensity in 2005 was close to our results. Ref (3)'s result was Shanghai's commercial energy intensity which was close to our commercial energy intensity. Ref (4) (Zhou and Lin, 2008)'s total building energy intensity in 2000 was 217.6 kwh/m^2 which was close to our result. From the comparison with other studies, we know that our results are reliable.

5.3. The energy-efficient building floor space

China implemented BEE work since the 1980s. The Mandatory

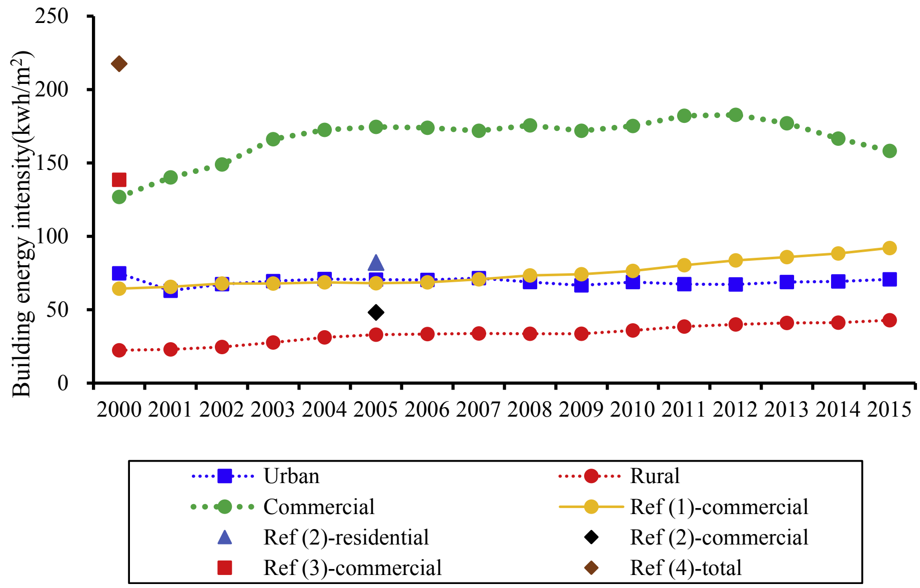

Fig. 11. Comparison with other studies on the energy intensity.

Civil Building Energy Efficiency Codes (MCBEE) has experienced three stages, with each stage representing mandatory codes designed to reduce building energy consumption by 30%, 50%, and 65% compared to buildings constructed during 1980–1981. The BEE design codes for the severe cold and cold regions, the hot summer and cold winter region, and the hot summer and warm winter region were first implemented in 1986, 2001, and 2003, respectively (Guo et al., 2016). The Ministry of Housing and Urban-Rural Development (MOHURD) of China released the *Design Code for Energy Efficiency of Public Buildings* (GB50189-2005) in 2005. Based on the time scales of the corresponding measures, we made the following assumptions. Commercial buildings constructed before 2005 are all regarded as buildings without performing BEE codes.

Fig. 12 shows that the residential buildings that have met the compliance rate at the construction stage increased from 0.2 billion m^2 in 2000 to 13.1 billion m^2 in 2015. The amount of floor space of the residential buildings without performing BEE codes grew steadily during 10th FYP period and trended downward during the 11th FYP period and 12th FYP period. Similarly, the commercial buildings that met the compliance rate rose from 0.1 billion m^2 in 2005 to 5.1 billion m^2 in 2015. The floor space of the Non-MCBEE commercial buildings saw a downward trend during the 11th FYP period and 12th FYP period. By the end of 2015, the Non-MCBEE residential and Non-MCBEE commercial buildings were 39.7 billion m^2 and 5.8 billion m^2, respectively. This indicates the effectiveness of building energy efficiency supervision work initiated by the MOUHORD since 2005. According to the 12th FYP of the building energy efficiency implemented by MOUHORD in 2016, the retrofit floor space of the existing residential and commercial buildings reached 1.1 billion m^2 and 0.1 billion m^2, respectively, by the end of 2015. This means that 38.6 billion m^2 of residential floor space and 5.7 billion m^2 of commercial floor space still need to be retrofitted in the future.

5.4. Comparison with other models and uncertainty analysis

5.4.1. Comparison with other models

(1) Analytical stock models (Aksözen et al., 2016). There are several analytical stock models such as MFA analysis (Hu et al., 2010a,b,c,d), leaching model (Voet et al., 2002). In these models, the demolitions are considered as a constant value, which do not change over time. Therefore, they would result in the deviations when being used in BFS estimation due to the long lifespan of buildings. (2) Dynamic stock models. In these models, the demolition information is always lacking. Authors commonly made a hypothesis on the average life span of buildings and distribution function for the demolitions (Bergsdal et al., 2007; Hong et al., 2016). Two key parameters are mean and standard deviation, which are always based on expert judgement. The estimation deviation can be narrowed by combing with cohort model with some renovation information (Aksözen et al., 2016). (3) Mortality models. These models do not need demolition rate, but need the longitudinal data (IvanM, 1994). Aiming to the lack of longitudinal data, the Kaplan-Merer estimator (KME) can be adopted to avoid this problem. It is a non-parametric approach which can be utilized with any distribution. The shortcoming of the KME method is that the curve is defined with the observed value, so it is difficult to fit a function (Aksözen et al., 2016). As for China's building stock, we introduced the *actual* per capita urban residential BFS to eliminate the incomplete statistic coverage. And then we adopted the improved building stock turnover model to estimate the BFS and demolitions by vintage to cover the gap of the unreliability of the statistics data and the lack of observed data.

5.4.2. Uncertainty analysis

The sensitivity analysis chart is shown in Fig. 13. The μ and σ are two key parameters, and the sensitivity analysis on these two parameters are show in Fig. 10. As shown in Fig. 10, if the value of the σ set to be equal to one third of the value of μ as mentioned in Section 3, the rural residential BFS is more sensitive to the mean life span parameter. When the μ increase one year, the BFS in 2015 will increase 2.51 Mm^2 averagely, and the urban residential BFS and commercial BFS would grow 1.33 and 0.58 Mm^2 respectively. If we keep the μ constant, the rural residential BFS is less sensitive to the parameter σ then urban and commercial BFS. It is noteworthy that

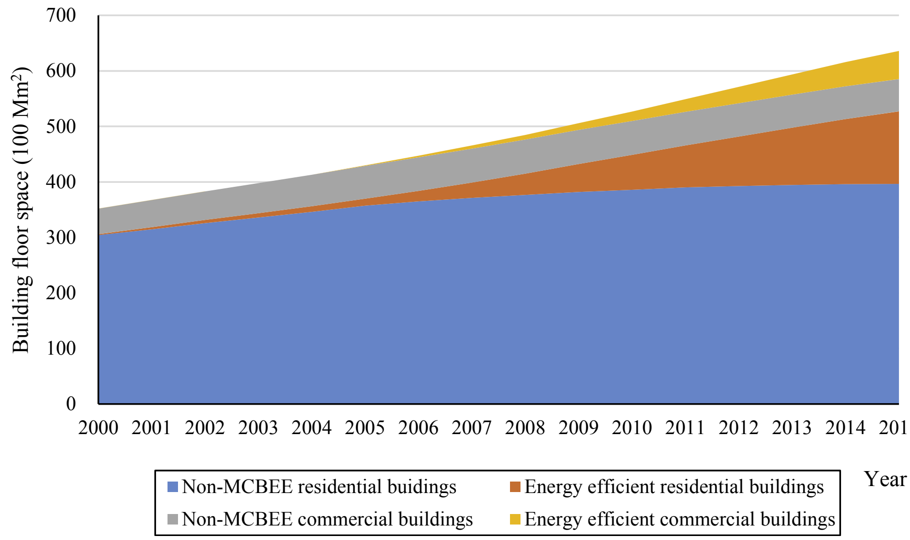

Fig. 12. The energy efficient and Non-MCBEE buildings from 2000 to 2015.

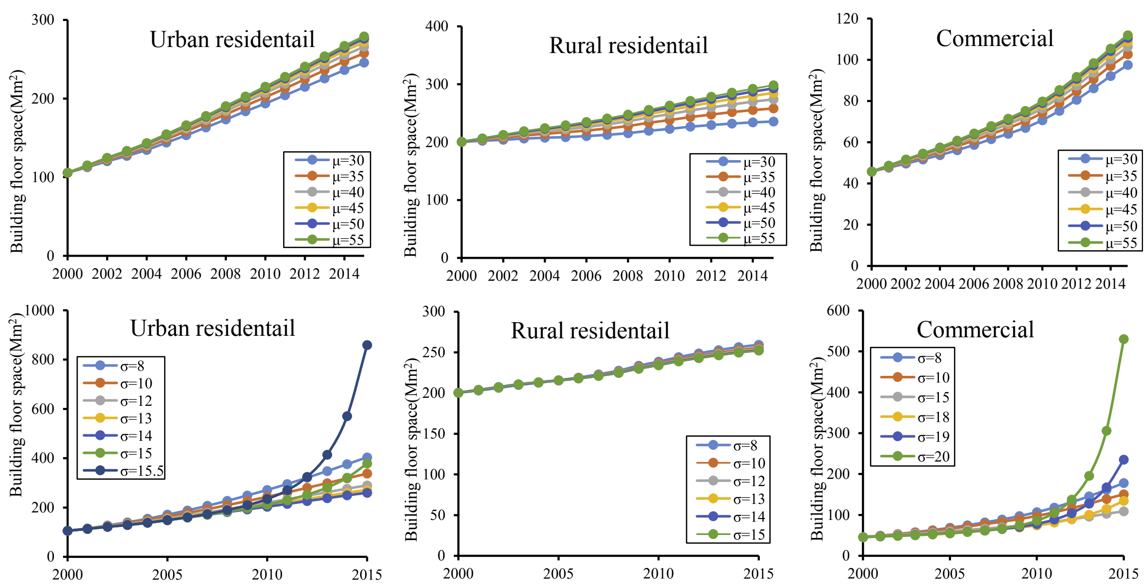

Fig. 13. Sensitivity analysis for the building floor space.

when the value of the σ exceeds 15, the urban residential BFS would grow dramatically. And when the σ exceeds 18, the commercial also shows significant growth. The reason might be the adjustment of the newly built BFS in our model aiming to eliminate the incomplete statistical caliber.

6. Conclusion

Accurately and objectively measuring BFS data is essential for predicting energy demand and carbon emission peak value in the building sector. It can help decision makers develop and enact effective energy efficient policies and work. However, China's building sector lacks authoritative and high-quality BFS data. More importantly, China has no unified BFS calculation method. This study systematically analyzed the *China Statistical Yearbook* in detail and then proposed a China BFS estimation method (CBFSM) based on the improved building stock turnover model. China's building stocks and demolition by type and vintage from 2000 to 2015 were derived using this method. The energy intensity and energy efficient buildings were also calculated. The main conclusions are as follows:

(1) China's current total building stock was 63.6 billion m^2 in 2015. Of this, the urban dwelling stock accounted for the largest amount (43%), followed by rural dwelling stock (40%) and commercial building stock (17%). In 2015, buildings constructed after 1990 accounted for more than 80% of the total building stock, and buildings constructed after 2000 represented 60.6% of the total building stock. This indicated that the large scale construction activities began when China entered new century.

(2) The total building stock in China witnessed a significant upward trend from 35.2 billion m^2 in 2000 to 63.6 billion m^2 in 2015. The annual growth rate of the BFS was 4.0% throughout 2000–2015. Both the urban residential stock and commercial stock more than doubled, although commercial

building stock just accounted for a smallest percentage, below 18%. During 2000 to 2015, the newly built buildings saw a fluctuation and increased from 1.9 billion m^2 in 2000 to 2.8 billion m^2 in 2015.

(3) The urban residential building energy intensity remained relatively stable throughout the whole period from 2000 to 2015. This implied the effectiveness of the supervision and inspection of energy efficient codes for newly-built buildings since 2005. From 2000 to 2015, the rural residential building energy intensity has increased more than twice, from 22.38 kwh/m^2 in 2000 to 48.32 kwh/m^2 in 2015, with an average annual increase of 5.5%. This is attributed to increased energy use demand resulting from the improve living conditions of rural residents, the transformation from non-commercial energy to commercial energy due the change of the traditional life style, and the lag of BEE work in rural areas. The commercial building energy intensity increased dramatically, annual growth rate 7.8%, during “10th FYP” period, remained relatively stable during “11th FYP” period and saw the downward trend during “12th FYP” period. This indicated the effectiveness of the BEE work for commercial building since 2005.

(4) By the end of 2015, the Non-MCBEE residential and Non-MCBEE commercial buildings were 39.7 billion m^2 and 5.8 billion m^2, respectively. This indicates the effectiveness of building energy efficiency supervision work initiated by the MOUHORD since 2005.38.6 billion m^2 of residential floor space and 5.7 billion m^2 of commercial floor space still need to be retrofitted in the future.

The contributions and implications of this study are as follows. The extensive analysis on the existing problems concerning the BFS associated statistical indicators in the *China Statistical Yearbook* can provide the readers worldwide a better and deeper insight in understanding the *China Statistical Yearbook*. The proposed model (CBFSM) can not only enrich the methods of calculating building stock and building demolition wastes data in Chinese construction field, it can also provide a very concise and practical means of acquiring consistent and defensible China building stock and demolition data for use by the government and local officials. These data can provide powerful technical support and evidence for the Chinese government to promote BEE work and carbon emission peak analysis.

In our future work, we will adopt a dynamic stock model to investigate the turnover of China's building floor space. We will estimate future construction, renovation and demolition flows in order to investigate possible scenarios for the evolution of material demand, energy consumption, as well as GHG emissions and wastes generations from China building stock towards 2050.

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Appendix

To validate the reliability of the estimation results, we need to compare our results with *China Population Census*. This is actually a multi-objective optimization issue. We need to ensure the sum of D_t^S and D_t^R are minimal to ensure the reliability of our results. In this optimization model, we need to give priority to minimizing the D_t^S which means ensuring the reliability of the building stock first. So, we assume ω_t equals 0.7 and ω_r equals 0.3. The multi-objective optimization model is shown as follows:

$$Min\ D(\mu, k_t) = \left(\omega_t \times ABS\left(D_t^S\right) + \omega_r \times ABS\left(D_t^R\right)\right)$$

$$\begin{cases} s.t.D_t^S = \dfrac{(Stock_t - Stock_{census})}{Stock_{census}} \times 100\% \\ D_t^R = \left(Ratio_t^{vin} - Ratio_{census}^{vin}\right) \times 100\% \\ New_t = New_t \times k_t \\ Retire_t^{vin} = Stock_{t-1}^{vin} \times \dfrac{P_t^{vin} - P_{t-1}^{vin}}{1 - P_{t-1}^{vin}} \\ P_t^{vin} = \dfrac{1}{\sqrt{2\pi}\sigma} \displaystyle\int_0^{lifetime_t^{vin}} e^{-\frac{\left(lifetime_t^{vin} - \mu\right)^2}{2\sigma^2}} dt \\ Stock_t = Stock_{t-1} - Retired_t + New_t \\ t \geq 2000\ t = 2000, \cdots, 2015 \\ k_t > 1 \\ 0 < \omega_t < 1; 0 < \omega_r < 1 \end{cases} \tag{A1}$$

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